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10 WAVEGUIDE FOR AN OPTICAL CIRCUIT AND METHOD OF
11 FABRICATION THEREOF

13 FIELD OF THE INVENTION

15 The present invention relates to a waveguide for an
16 optical circuit, and a method of fabrication thereof

18 The method relates in particular to the fabrication of
19 a waveguide for an optical circuit with smoothed
20 waveguide core boundaries. More specifically, the
21 method relates to the fabrication of a rounded,
22 elliptical or circular waveguide core by the isotropic
23 diffusion of dopants in a core layer of a
24 phosphosilicate waveguide wafer, such that the diffused
25 core layer forms the circular waveguide core. In this
26 manner, a core may be formed which is symmetric about
27 the core axis.

29 This diffusion is thermally promoted either during the
30 deposition of an upper cladding layer or by subsequent
31 thermal processing of the waveguide wafer.

33 BACKGROUND OF THE INVENTION

35 The general process of fabricating a glass waveguide
36 for optical circuits comprises forming at least one
37 buffer layer, e.g. a thermal oxide layer, on a silicon
38 wafer substrate. Additional buffer layers and/or at

1 least one lower cladding layers may then be formed on
2 top of the buffer layer. A core layer composed of a
3 doped silica film is then formed on top of the buffer
4 layer or lower cladding layer.

6 The core layer is then etched, for example, by reactive
7 ion techniques, to form a square or rectangular
8 waveguide or other suitable cross-sectional profile.
9 The etched core is then embedded by an upper cladding
10 layer. The core layer refractive index is usually
11 higher than that of the surrounding layers. This
12 concentrates the propagation of light in the core
13 layer.

14

15 Planar channel waveguides are usually formed using dry
16 etch methods to produce waveguides with square or
17 rectangular cross-sections. Such angular waveguides
18 have several disadvantages, in particular the
19 geometrical mismatch between the waveguides and optical
20 fibres in an optical circuit. The production of channel
21 waveguides with a circular cross-section is
22 particularly advantageous in that this increases the
23 transmission efficiency between the waveguide and the
24 rest of an optical circuit.

25

26 Channel waveguides are also susceptible to scatter loss
27 (Mie scattering) due to imperfections in their
28 sidewalls. This is reduced by smoothing the profile of
29 the waveguide and this provides low propagation loss in
30 the waveguides.

31

32 Circular optical waveguides are known in principle (for
 33 example, see Sun et al., "Silica-based circular cross-
 34 sectioned channel waveguides", IEEE Photonics
 35 Technology Letters, 3, p.p. 238-240, 1991). Sun et
 36 al., disclose large dimension (~50 μ m) GeO₂ doped silica

1 waveguides which are reactive ion etched to form
2 rectangular channel cross-sections. This method
3 involves depositing a lower cladding layer with a
4 reduced amount of Germanium doped silicon on to the
5 wafer substrate prior to the deposition of a core
6 layer. When the wafer is placed in the selective wet
7 etch, the lower cladding layer is etched at a much
8 faster rate to form a pedestal underneath the core
9 region.

10

11 According to Sun et al., the waveguide can then be
12 heated above the core softening temperature so that the
13 surface tension of the glass functions to round the
14 waveguide core. Such wet etching techniques are time
15 consuming and moreover, do not offer truly circular
16 cross sections as the core cannot be rounded at the
17 interface between the core layer and the pedestal
18 (i.e., the lower cladding layer lying directly beneath
19 the core).

20

21 The current invention in contrast relies on the
22 mobility of dopant ions in a square or rectangular
23 etched core to migrate outwards into both upper and
24 lower cladding layers. This forms waveguides which
25 have substantially smoothed boundary walls, in
26 particular the side walls are smoothed.

27

28 Further diffusion rounds the core region, and providing
29 the diffusion is sufficiently isotropic the core region
30 becomes sufficiently rounded to form a circular
31 waveguide. This diffusion is thermally promoted either
32 during the consolidation of the upper cladding layer or
33 during subsequent thermal processing. By selecting the
34 composition of the upper and lower cladding layers, the
35 refractive indexes and consolidation temperatures can
36 be chosen to modify the rate at which the core dopant

DOPANT ION SMOOTHING

1 ions diffuse into each layer and the ellipticity of the
2 resulting waveguide core accordingly adjusted.
3

4

5 SUMMARY OF THE INVENTION
6

7 According to a first aspect of the present invention,
8 there is provided a waveguide for an optical circuit
9 comprising:

10 a substrate;

11 a doped lower cladding layer;

12 a doped waveguide core formed on the lower
13 cladding layer; and

14 a doped upper cladding layer embedding the
15 waveguide core;

16 wherein the waveguide core includes mobile dopant
17 ions which have diffused into the upper cladding layer
18 and the lower cladding layer to form an ion diffusion
19 region around said waveguide core such that the
20 waveguide core boundary walls are substantially smooth.
21

22 Preferably, the waveguide further includes a buffer
23 layer formed on the substrate and wherein the lower
24 cladding layer is formed on the buffer layer. The
25 substrate may comprise silicon and/or silica and/or
26 sapphire. The buffer layer may include a thermally
27 oxidised layer of the substrate.
28

29 Preferably, the buffer layer comprises doped silica.
30

31 Preferably, the thickness of the buffer layer is in the
32 range 0.2 μ m to 20 μ m.
33

34 The lower cladding layer may comprise doped silica.
35 The lower cladding layer may include at least one
36 Phosphorus oxide and/or at least one Boron oxide.

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1 Preferably, the lower cladding layer includes at least
2 one Phosphorus oxide and at least one Boron oxide,
3 wherein the Phosphorus oxide to Boron oxide ratio is
4 such that the lower cladding layer refractive index is
5 substantially equal to the refractive index of the
6 buffer layer.

7

8 The lower cladding layer may include doped silica, at
9 least one Phosphorus oxide and at least one Boron
10 oxide, wherein the silica:Phosphorus oxide:Boron oxide
11 ratio is in the range of 75 to 95 wt% silica:1 to 7 wt%
12 Phosphorus oxide:4 to 18 wt% Boron oxide.

13

14 Preferably, the lower cladding layer has a
15 silica:Phosphorus oxide:Boron oxide ratio in the range
16 of 80 to 90 wt% silica:2.5 to 6 wt% Phosphorus
17 oxide:7.5 to 14 wt% Boron oxide.

18

19 More preferably, the lower cladding layer has a silica;
20 to Phosphorus oxide; to Boron oxide ratio of 82 wt%
21 silica; to 5 wt% Phosphorus oxide; to 13 wt% Boron
22 oxide.

23

24 Preferably, the thickness of the lower cladding layer
25 is 1 μ m to 20 μ m.

26

27 The waveguide core may comprise doped silica. The
28 mobile dopant ions of the waveguide core may include
29 Phosphorus and/or Fluorine and/or compounds of these
30 elements. Dopant ions of the waveguide core may
31 include Phosphorus and/or Fluorine and/or Aluminium
32 and/or Boron and/or Germanium and/or Tin and/or
33 Titanium and/or compounds of these elements.

34

35 Preferably, the waveguide core includes Phosphorus
36 oxide and/or Boron oxide. More preferably, the

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1 waveguide core comprises P_2O_5 - SiO_2 .

2

3 Preferably, the refractive index of the waveguide core
4 differs from that of the lower cladding layer by at
5 least 0.05%.

6

7 Preferably, the waveguide core includes silica, and at
8 least one Phosphorus oxide, wherein the silica to
9 Phosphorus oxide ratio is in the range of 75 to 95 wt%
10 silica to 5 to 25 wt% Phosphorus oxide.

11

12 More preferably, the waveguide core has a silica to
13 Phosphorus oxide ratio of 80 wt% silica to 20 wt%
14 Phosphorus oxide.

15

16 Preferably, the thickness of the waveguide core is in
17 the range $2\mu m$ to $60\mu m$.

18

19 More preferably, the thickness of the waveguide core is
20 $6\mu m$.

21

22 Preferably, the lower cladding layer and the upper
23 cladding layer refractive indices are substantially
24 equal. The lower cladding layer and the upper cladding
25 layer may comprise the same material.

26

27 Preferably, the waveguide core has a mobile ion dopant
28 concentration higher than the mobile ion dopant
29 concentration of the lower cladding layer or the upper
30 cladding layer.

31

32 Preferably, the ion diffusion region is isotropic with
33 respect to the waveguide core.

34

35 Preferably, the ion diffusion region surrounding the
36 waveguide core forms a substantially rounded waveguide

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1 core.

2

3 More preferably, the rounded waveguide core is
4 elliptical or circular in cross-section.
5

3

6 According to a second aspect of the invention, there is
7 provided a method of fabricating a waveguide comprising
8 the steps of: providing a substrate; forming a doped
9 lower cladding layer; forming a doped core layer on the
10 lower cladding layer; forming a waveguide core from the
11 core layer; forming a doped upper cladding layer to
12 embed the waveguide core; wherein mobile ion dopants
13 included in the core layer undergo diffusion into the
14 surrounding upper cladding layer and lower cladding
15 layer to form an ion diffusion region around the
16 waveguide core such that the waveguide core boundary
17 walls are substantially smooth.

18

19 The method may include the step of forming a buffer
20 layer on the substrate. The lower cladding layer may
21 be formed on said buffer layer. The steps of forming
22 each of the lower cladding layer, the core layer and
23 the upper cladding layer may comprise the steps of:
24 depositing each layer; and at least partially
25 consolidating each layer.

26

27 Preferably any of the lower cladding layer, the core
28 layer and the upper cladding layer partially
29 consolidated after deposition is fully consolidated
30 with the full consolidation of any other of the lower
31 cladding layer, the core layer or the upper cladding
32 layer.

33

34 Preferably, the diffusion of mobile ion dopants in the
35 core layer occurs during the consolidation of the lower
36 cladding layer and/or the upper cladding layer.

1 The method may further comprise at least one thermal
2 processing step after the formation of the upper
3 cladding layer, wherein during said thermal processing
4 of the waveguide the mobile ion dopants in the core
5 layer undergo diffusion into the surrounding layers.
6 The substrate may comprise silicon and/or silica and/or
7 sapphire. The buffer layer may include a thermally
8 oxidised layer of the substrate. The buffer layer may
9 comprise doped silica.

10

11 Preferably, the thickness of the buffer layer formed is
12 in the range of $0.2\mu\text{m}$ to $20\mu\text{m}$. The lower cladding
13 layer may comprise doped silica. The lower cladding
14 layer may include at least one Phosphorus oxide and/or
15 Boron oxide. The lower cladding layer may include at
16 least one Phosphorus oxide and at least one Boron
17 oxide, wherein the Phosphorus oxide to Boron oxide
18 ratio is such that the lower cladding layer refractive
19 index is substantially equal to the refractive index of
20 the buffer layer.

21

22 Preferably, the lower cladding layer includes silica,
23 at least one Phosphorus oxide and at least one Boron
24 oxide, wherein the silica; to Phosphorus oxide; to
25 Boron oxide ratio in the range of 75 to 95 wt% silica;
26 to 1 to 7 wt% Phosphorus oxide; to 4 to 18 wt% Boron
27 oxide.

28

29 Preferably, the lower cladding layer has a silica; to
30 Phosphorus oxide; to Boron oxide ratio in the range of
31 80 to 90 wt% silica; to 2.5 to 6 wt% Phosphorus oxide;
32 to 7.5 to 14 wt% Boron oxide.

33

34 More preferably, the lower cladding layer has a silica;
35 to Phosphorus oxide; to Boron oxide ratio of 82 wt%
36 silica; to 5 wt% Phosphorus oxide; to 13 wt% Boron

1 oxide.

2

3 Preferably, the thickness of the lower cladding layer
4 is $1\mu\text{m}$ to $20\mu\text{m}$.

5

6 Preferably, the core layer comprises doped silica. The
7 mobile dopant ions of the waveguide core may include
8 Phosphorus and/or Fluorine and/or compounds of these
9 elements. The dopant ions of the waveguide core may
10 include Phosphorus and/or Fluorine and/or Aluminium
11 and/or Boron and/or Germanium and/or Tin and/or
12 Titanium and/or compounds of these elements.

13

14 The core layer may include Phosphorus oxide and/or
15 Boron oxide.

16

17 Preferably, the core layer comprises $\text{P}_2\text{O}_5\text{-SiO}_2$.

18

19 Preferably, the refractive index of the waveguide core
20 differs from that of the lower cladding layer by at
21 least 0.05%.

22

23 Preferably, the waveguide core includes silica and at
24 least one Phosphorus oxide, wherein the silica to
25 Phosphorus oxide ratio is in the range of 75 to 95 wt%
26 silica to 5 to 25 wt% Phosphorus oxide.

27

28 More preferably the waveguide core has a silica to
29 Phosphorus oxide ratio of 80 wt% silica to 20 wt%
30 Phosphorus oxide.

31

32 Preferably, the thickness of the waveguide core is in
33 the range $2\mu\text{m}$ to $60\mu\text{m}$.

34

35 More preferably, the thickness of the waveguide core is
36 $6\mu\text{m}$.

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1 Preferably, the lower cladding layer and said buffer
2 layer are formed substantially in the same step.
3

4 Preferably, the consolidation of the lower cladding
5 layer is at a temperature or temperatures in the range
6 950°C to 1400°C.
7

8 Preferably, the consolidation of the lower cladding
9 layer is at a temperature or temperatures in the range
10 1100°C to 1350°C.
11

12 Preferably, the consolidation of the core layer is at a
13 temperature or temperatures in the range 950°C to
14 1400°C.
15

16 More preferably, the consolidation of the core layer is
17 at a temperature or temperatures in the range 1100°C to
18 1385°C.
19

20 Preferably, the consolidation of the upper cladding
21 layer is at a temperature or temperatures in the range
22 950°C to 1400°C.
23

24 More preferably, the consolidation of the upper
25 cladding layer is at a temperature or temperatures in
26 the range 1100°C to 1350°C.
27

28 The temperature or temperature range at which the lower
29 cladding layer is consolidated may be greater than the
30 temperature or temperature range at which the core is
31 consolidated. The temperature or temperature range at
32 which the upper cladding layer is consolidated may be
33 substantially equal to the temperature or temperature
34 range at which the core layer is consolidated.
35

36 At least one of the lower cladding layer, the core

1 layer, and the upper cladding layer may be deposited by
2 a Flame Hydrolysis Deposition process and/or Chemical
3 Vapour Deposition process. The Chemical Vapour
4 Deposition process may be a Low Pressure Chemical
5 Vapour Deposition process or a Plasma Enhanced Chemical
6 Vapour Deposition process.

7

8 Preferably, the consolidation is by fusing using a
9 Flame Hydrolysis Deposition burner. Alternatively, the
10 consolidation may be by fusing in a furnace.

11

12 Preferably, the step of fusing the lower cladding layer
13 and the step of fusing the core layer are performed
14 simultaneously.

15

16 Preferably, the waveguide core formed from the core
17 layer is square or rectangular in cross-section.

18

19 The waveguide core may be formed from the core layer
20 using a dry etching technique and/or a
21 photolithographic technique and/or a mechanical sawing
22 process.

23

24 The dry etching technique may comprise a reactive ion
25 etching process and/or a plasma etching process and/or
26 an ion milling process.

27

28 Preferably, the diffusion of the said mobile dopant
29 ions from the waveguide core is isotropic.

30

31 Preferably, the diffusion of the said mobile dopant
32 ions from the waveguide core swells the boundary walls
33 of the waveguide core.

34

35 More preferably, diffusion of the said mobile dopant
36 ions swells the boundary walls of the waveguide core to

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1 form a substantially rounded waveguide core.
2

3 The rounded waveguide core formed may be elliptical or
4 circular in cross-section.
5

6 The smoothing of the walls reduces scattering losses
7 and lowers the propagation losses for the waveguides.
8 Coupling losses between optical circuits and optical
9 fibre are also reduced due to the improved geometry of
10 the waveguide core. For example, the enhanced
11 roundedness of the core of the waveguide enables it to
12 be coupled more efficiently to optical fibre which has
13 an appropriate circular or elliptical cross-section.
14

15

16 DESCRIPTION OF THE DRAWINGS
17

18 Embodiments of the present invention will now be
19 described by way of example only with reference to the
20 accompanying drawings in which:-
21

22 Fig. 1 is a cross-sectional diagram of a conventionally
23 rounded waveguide;
24

25 Figs. 2A to 2E are a cross-sectional diagrams showing
26 stages in the fabrication of a rounded waveguide
27 according to the present invention;
28

29

30 DETAILED DESCRIPTION OF THE INVENTION
31

32 With reference to the drawings, there is described now
33 a waveguide for an optical circuit and a method of
34 fabrication thereof according to the present invention.
35

36 A waveguide produced by conventional techniques which

1 can partially round the cross-section of the core layer
2 of a waveguide is shown in Fig.1. This illustrates such
3 a waveguide 1 with a rounded core upper cross-section 2
4 and flat base 3 supported by a pedestal 4 embedded in a
5 cladding layer 5 as might be formed by the conventional
6 method of *Sun et al.*

7

8 The present invention provides a waveguide which does
9 not exhibit the flat base 3 shown in Fig.1. Various
10 stages in the method of fabricating such a waveguide
11 will now be described with reference to Figs. 2A to 2E.
12

13 Fig. 2A is a schematic diagram showing the preliminary
14 stages in a method of fabricating a waveguide with an
15 elliptical or rounded cross-section from a silicon
16 wafer according to a first embodiment of the invention.
17

18 In this embodiment, a silicon substrate 6 is covered
19 with a buffer layer 7 comprising thermally oxidised
20 silicon. In alternative embodiments of the invention,
21 the substrate 6 comprises silica and sapphire and the
22 buffer layer 7 further includes at least one Phosphorus
23 oxide and/or Boron oxide. The thickness of the
24 thermally oxidised silicon buffer layer 7 ranges
25 between 0.2 μm and 20 μm .

26

27 A lower cladding layer 8, doped with Phosphorus and
28 Boron ions (although other dopants may be
29 substituted/added in alternative embodiments of the
30 invention, in which for example, the lower cladding
31 layer may be doped primarily with Phosphorus and Boron)
32 and having a refractive index matched to the buffer
33 layer 7, is then deposited using a Flame Hydrolysis
34 Deposition (FHD) process on to the buffer layer 7, and
35 is consolidated either in an electrical furnace or by
36 using an FHD burner.

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1 By way of example, the FHD process used for deposition
2 of the lower cladding layer 8 can employ the following
3 input feed flow rates for the feed gases:-
4 Shroud gas 5 litres/min; O₂ 4 litres/min;
5 H₂ 2 litres/min; SiCl₄, carrier gas 0.15 litres/min;
6 PCl₃, carrier gas 0.04 litres/min;
7 BC₁, carrier gas 0.09 litres/min. The halides are
8 carried, for example, by an N₂ carrier gas, and the
9 shroud gas can, for example, be N₂.
10

11 In this embodiment of the invention, the lower cladding
12 layer 8 formed comprises silica, Phosphorus oxide, and
13 Boron oxide; for example SiO₂-P₂O₅-B₂O₃. In alternative
14 embodiments, the lower cladding layer 8 may contain
15 dopant ions in addition to SiO₂-P₂O₅-B₂O₃. The doping
16 levels for the silica, Phosphorus oxide and Boron oxide
17 in the lower cladding layer 8 are 82 wt% silica, 5 wt%
18 Phosphorus oxide and 13 wt% Boron oxide. Varying the
19 flow rates of the input gases in the FHD burner results
20 in different doping levels. In other embodiments of
21 the invention, the preferred doping levels range
22 between 75 to 95 wt% silica, 1 to 7 wt% Phosphorus
23 oxide and 4 to 18 wt% Boron oxide, or alternatively
24 range between 80 to 90 wt% silica, 2.5 to 6 wt%
25 Phosphorus oxide, and 7.5 to 14 wt% Boron oxide. Other
26 suitable cladding layer materials may be used and
27 suitably doped in alternative embodiments of the
28 invention.
29

30 The lower cladding layer 8 is consolidated by fully
31 fusing the layer in an electric furnace at a
32 temperature of 1250°C, which is in a preferred range of
33 temperatures of between 1100°C to 1350°C.
34

35 In alternative embodiments, the lower cladding layer 8
36 is deposited using an FHD process and can be

1 consolidated at different temperatures within a range
2 of temperatures of between 950°C to 1400°C.
3

4 In a further alternative, the lower cladding layer 8 is
5 deposited by a Flame Hydrolysis Deposition (FHD)
6 process and partially consolidated at this stage and
7 fully consolidated subsequently.
8

9 The thickness of the lower cladding layer 8 deposited
10 is 2 μm but can range between 1 μm and 20 μm .
11

12 In alternative embodiments, where no buffer layer is
13 employed, the lower cladding layer 8 can be formed
14 directly on top of the substrate 6.
15

16 A core layer 9 comprising Phosphorus oxide and silica,
17 for example, $\text{P}_2\text{O}_5\text{-SiO}_2$ is then formed on the lower
18 cladding layer 8. The refractive index of the core
19 layer 9 differs from that of the lower cladding layer 8
20 by 0.75%, and may differ by a value within the range of
21 0.05 % to 2 %.
22

23 By way of example, the FHD process used for deposition
24 of the core layer 9 can employ the following input feed
25 flow rates for the feed gases:-
26

27 Shroud gas 5 litres/min; O_2 6 litres/min;
28 H_2 4 litres/min; SiCl_4 carrier gas 0.15 litres/min;
29 PCl_3 carrier gas 0.018 litres/min. The halides are
30 carried, for example, by an N_2 carrier gas, and the
shroud gas can, for example, be N_2 .
31

32 The core layer 9 is consolidated by fully fusing the
33 layer in an electric furnace at a temperature of
34 1200°C, which is in a preferred range of temperatures
35 of between 1100°C to 1385°C.
36

1 In alternative embodiments, the core layer 9 is
2 deposited using an FHD process and can be consolidated
3 at different temperatures within a range of
4 temperatures of between 950°C to 1400°C.
5

6 In a further alternative, the core layer 9 is partially
7 consolidated at this stage and consolidated
8 subsequently.
9

10 The dopant levels for the core layer 9 are 80 wt%
11 silica and 20 wt% Phosphorus oxide in the preferred
12 embodiment. In alternative embodiments, the input
13 gases into the FHD burner are varied to give core
14 dopant levels between 75 to 95 wt% silica and 5 to 25
15 wt% Phosphorus oxide respectively. The thickness of
16 the core layer deposited is 6 μm but can range between
17 2 μm and 60 μm .
18

19 The core layer mobile ion dopants include Phosphorus
20 ions but could, for example, include Fluorine ions. In
21 alternative embodiments, the core layer 9 is doped
22 Phosphorus and co-doped with ions with desired
23 properties to effect reduction of the sintering
24 temperature and/or to effect increase of the core layer
25 refractive index. The co-dopants may be selected from
26 the group comprising Aluminium, Boron, Germanium, Tin
27 and/or Titanium. For example, co-doping with Germanium
28 reduces the sintering temperature and raises the silica
29 based core layer 9 refractive index so that the
30 refractive index is higher than the refractive index of
31 the lower cladding layer 8 on top of which the core
32 layer 9 is deposited.
33

34 The lower cladding layer 8 is susceptible to
35 interdiffusion from the dopant ions from the core layer
36 9. In contrast, the buffer layer 7 acts as a barrier

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1 against interdiffusion.

2

3 Fig. 2B shows the subsequent stage in the method of
4 fabricating an optical waveguide in which the core
5 layer 9 is redefined by removing regions 10 by a
6 reactive ion etching (RIE) technique to form a square
7 waveguide core 11. In general, a square or rectangular
8 waveguide core 11 whose dimensions range from 2 μm to
9 60 μm will be suitable in the method of fabricating an
10 optical waveguide, preferred dimensions being such as
11 to give a waveguide core 11 of 6 μm x 6 μm .

12

13 Alternative techniques for forming a square or
14 rectangular waveguide core 11 can be used, or a
15 combination of techniques. For example, dry etching
16 techniques (e.g. reactive ion etching, ion milling,
17 and/or plasma etching processes), a photolithographic
18 technique, and/or a mechanical sawing process may be
19 used.

20

21 Subsequently, the waveguide core 11 is surrounded by,
22 or embedded in, an upper cladding layer 12 (as shown in
23 Fig. 2C) comprising Phosphorus oxide, Boron oxide and
24 silica. Preferably, the upper cladding layer 12 has
25 the same composition as the lower cladding layer 8
26 (P_2O_5 - B_2O_3 - SiO_2) and the same refractive index.

27 Alternatively, the upper cladding layer 12 can have a
28 different composition from the lower cladding layer 8
29 but can have substantially the same refractive index.
30 The upper cladding layer 12 can be deposited using the
31 same input gas flow parameters into the FHD apparatus
32 as for the lower cladding layer 8.

33

34 The upper cladding layer 12 is then consolidated in a
35 furnace and by adjusting the duration and temperature
36 of the heat treatment the amount of diffusion of the

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1 dopant ions in the waveguide core 11 can be adjusted.
2

3 The upper cladding layer 12 is consolidated by fully
4 fusing the upper cladding layer 12 in an electric
5 furnace for about 90 minutes at a minimum temperature
6 of 1050°C and preferably at a temperature of 1200°C,
7 which is in a preferred range of temperatures of
8 between 1100°C to 1250°C.
9

10 The consolidation temperature of the upper cladding
11 layer 12 is a minimum of 1050 °C for the given co-
12 dopant levels. In alternative embodiments, for other
13 co-dopant levels, the upper cladding layer 12 is
14 deposited using an FHD process and can be consolidated
15 at different temperatures within a range of
16 temperatures of between 950°C to 1250°C. By suitably
17 varying the co-dopant levels in the upper cladding
18 layer 12 the consolidation temperature can be reduced
19 to below 950°C.
20

21 Fig. 2D shows how the consolidation temperature of the
22 upper cladding layer 12 promotes diffusion of the
23 mobile core dopant ions into the upper cladding layer
24 12 and lower cladding layer 8. The composition of the
25 upper and lower cladding layers 8 and 12 gives a
26 diffusion length of 2 μ m when the consolidation
27 temperature of the core layer 9 and upper cladding
28 layer 12 is 1200°C. More typically, the diffusion
29 length is between the range of 0.1 μ m to 3 μ m for the
30 preferred ranges of consolidation temperatures.
31

32 The upper cladding layer 12 is consolidated at a
33 temperature which is the same as or greater than a
34 temperature which promotes efficient diffusion of the
35 waveguide core 11.
36

1 The ion dopant concentration in the lower cladding
2 layer 8 and upper cladding layer 12 is chosen so that
3 the waveguide core 11 has a higher concentration of
4 dopant ions to promote diffusion of the waveguide core
5 11 dopant ions into the lower cladding layer 8 and
6 upper cladding layer 12. In the preferred embodiment,
7 the diffusion of the mobile ion dopants in the
8 waveguide core 11 into the surrounding cladding layers
9 8 and 12 occurs during consolidation of the upper
10 cladding layer 12, during which the core boundaries of
11 the waveguide core 11 are rounded and a waveguide 13 is
12 formed which is circular in cross-section.
13

14 In an alternative embodiment, subsequent thermal
15 processing after the consolidation of the upper
16 cladding layer 12 promotes diffusion of the mobile ion
17 dopants in the waveguide core 11 into the surrounding
18 cladding layers 8 and 12.
19

20 Fig. 2E shows the resulting rounded waveguide 13.
21

22 In other embodiments of the invention, a silica based
23 waveguide core 11 may be doped with Phosphorus and
24 Germanium to raise the refractive index of the
25 waveguide core 11 and to reduce the consolidation
26 temperature of the waveguide core 11. Alternative
27 techniques may be used to redefine the waveguide core
28 11 from the core layer 9; e.g. photolithographic,
29 plasma etching processes, ion milling process,
30 mechanical sawing process, and RIE processes.
31

32 In other embodiments, the waveguide core 11 may
33 comprise more than one core layer 9. Such core layers
34 9 could be chosen to have substantially the same
35 refractive index but differ in material composition.
36

1 Other embodiments of the invention may require
2 additional interdiffusion upper cladding layers 12 and
3 lower cladding layers 8 to be deposited above and/or
4 below the waveguide core 11. To promote isotropic
5 diffusion, the lower cladding layers 8 may have the
6 same composition and/or the same refractive index as
7 that of the upper cladding layers 12. The isotropy of
8 the refractive index surrounding the waveguide core 11
9 promotes circular diffusion and a circular waveguide
10 core 13 results.

11

12 In other embodiments, a Chemical Vapour Deposition
13 (CVD) method, or a Plasma Enhanced Chemical Vapour
14 Deposition (PECVD) method, or a combination of these
15 methods can be used to form the cladding layers 8 and
16 12 and the core layer 9. Subsequent thermal processing
17 of the waveguide promotes diffusion of ion dopants from
18 the waveguide core 11 into the surrounding upper
19 cladding and lower cladding layers 8 and 12.

20

21 In other embodiments, the lower cladding layer 8 may be
22 only partially consolidated before the core layer 9 is
23 deposited thereon and fully consolidated when the core
24 layer 9 is consolidated. Furthermore, the waveguide
25 core 11 may only be partially consolidated when the
26 upper cladding layer 12 is formed thereon and may be
27 fully consolidated when the upper cladding layer 12 is
28 consolidated. Also, the FHD burner can be used for
29 fusing by passing the burner over the waveguide to fuse
30 the lower cladding and upper cladding layers 8 and 12
31 and to fuse the core layer 9.

32

33 While several embodiments of the present invention have
34 been described and illustrated, it will be apparent to
35 those skilled in the art once given this disclosure
36 that various modifications, changes, improvements and

1 variations may be made without departing from the
2 spirit or scope of this invention.

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